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DETERMINATION OF ELASTIC PROPERTIES OF IN-SITU ROCKS IN PERMAFR--ETC(U)
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Seismic prospecting methods applied in permafrost regions for determining the elastic characteristics (Modulus of elasticity, shear, and Poisson's ratio) of in-situ rocks and soils are substantiated. Peculiar wave patterns established by seismic prospecting in the arctic regions are examined. Typical wave patterns are analysed using the ultrasonic test data obtained on three-dimensional models of natural materials.

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DETERMINATION OF ELASTIC PROPERTIES OF IN-SITU ROCKS IN PERMAFROST REGIONS

Moscow IZVESTIYA VSESOYUZNOGO NAUCHNO-ISSLEDOVATEL'SKOGO INSTITUTA GIDROTEKHNIKI in Russian No 106, 1974 pp 249-263 manuscript received 26 Oct 73

[Article by O. K. Voronkov and V. I. Marov]

1. The Task of the Investigations

[Text] To calculate the dynamic elastic modulus E_d, Poisson's ratio μ_d, the shear modulus G_d and other characteristics of the elasticity of rocks it is necessary, besides the longitudinal wave velocity v_p, to know the transverse wave velocity v_s or the Rayleigh wave velocity v_R. Whereas the determination of v_s and v_R during seismoacoustic observations in mountain workings (shafts and wells) causes no difficulties in principle, during engineering seismic surveying on the day surface the determination of v_s and v_R involves a number of difficulties. In particular, in a permafrost region the presence of a high-velocity layer of frozen unconsolidated deposits in situ on bedrock excludes the possibility of obtaining $P_1S_2P_1$ and $P_1S_2S_1$ waves (exchange on the boundary of unconsolidated and solid rocks) -- intensive oscillations, registered with certainty in a number of regions where there is an absence of frost [7,3]. It is impossible to form those types of waves at $v_{p_1} > v_{s_2}$.

The nature of waves registered in each new region of investigations is determined by a large group of kinematic and acoustic characteristics, namely: the absolute wave velocities, the ratios of the velocities of different waves, the relative intensity, the ratios of the oscillation periods, the absorption coefficients and decrements, etc. By constructing variational curves or histograms for a statistical series of each of those signs one can determine their average values, and also the basic range of variation of the corresponding characteristics. In addition, other characteristics of the recording of waves are used: the traceability in the region of first or subsequent arrivals, the characteristic shape of the travel-time curve, etc. Comparisons with theoretical seismograms, etc, are also used. The nature of the waves is usually determined for the region of the work as a whole. As a rule, the nature of the waves cannot be established for local parts of that region. Therefore it is very important to know how given geological factors which vary within a given region (the thickness of deposits, their thawed or frozen state, etc) influence the properties of the wave field.

Seismic prospecting investigations (engineering and ore seismic prospecting) in a permafrost region have established that the most intense wave on the seismograms is the Rayleigh wave registered in "second arrivals" -- after longitude refracted waves. With respect to an overwhelming majority of the cases of engineering and ore seismic prospecting it can be regarded as a Rayleigh wave in a layer (unconsolidated deposits) on a half-space (bedrock is solid rock). The phase velocity of such a wave depends on a number of factors (the elasticity and density of the layer and half-space, the layer thickness and the wave length. Therefore, before using the experimental values of v_R obtained in field seismic prospecting investigations, for the calculation of E_d, μ_d, etc, of unconsolidated and solid rocks it is necessary to take into consideration quantitatively the influence of the enumerated factors on the phase velocity v_R.

In order to study the wave field registered during the seismic prospecting of small depths in regions of the Extreme North and permafrost an ultrasonic modeling was carried out on a three-dimensional model. Besides that, to study the dispersion of the velocity of Rayleigh waves in a layer on a half-space the theoretical dispersion curves were calculated and an analysis was made of the field seismic prospecting material obtained in permafrost regions of the Northeast of the USSR (the basins of the Indigirka, Vilyuy, Kolyma and Tatta rivers).

2. Characteristics of the Wave Picture According to Data of Three-Dimensional Ultrasonic Modeling (Layer on a Half-space)

To study the wave picture with reference to the conditions of permafrost regions the authors conducted an ultrasonic modeling of the wave picture by the method of longitudinal profiling zz. The profiling was carried out both from the surface of the layer and from the surface of the half-space (Figure 1). In the general case the three-dimensional model represented a layer (or two layers) of different thickness, composition and state on the half-space. The materials for the making of models were natural, particularly during the creation of layers use of made of water (v_p = 1450 m/sec, density δ = 1 g/cc), ice (v_p = 3650 m/sec, δ = 0.91 g/cc), frozen strongly icy loam (v_p = 3700 m/sec, v_R = 2000 m/sec, δ = 1.9 g/cc, and frozen ice-saturated sand (v_p = = 4000 m/sec, v_R = 2400 m/sec, δ = 1.85 g/cc).

The half-space is a granite block set on porolon and placed in a hydrolyzed vessel. The block dimensions were 430 x 190 x 80 mm; the wave velocities along the face length were:

	v_p	v_R
- in the dry state	4210 m/sec	2650 m/sec
- in the water-saturated state	5350 "	2820 "
- in the ice-saturated state	6000 "	3200 "

Let us examine the questions of similarity of the model (m) and nature (n).

As is known [5], the velocity criterion of similarity is $C = \frac{v_{p(n)}}{v_{p(m)}} = \frac{v_{s(n)}}{v_{s(m)}}$ which means equality of the Poisson's factors $\mu_{(n)} = \mu_{(m)}$. The density criterion $C_\delta = \frac{\delta_{(n)}}{\delta_{(m)}}$. For the models in our experiments C_v = 1 and C_δ = 1 and,

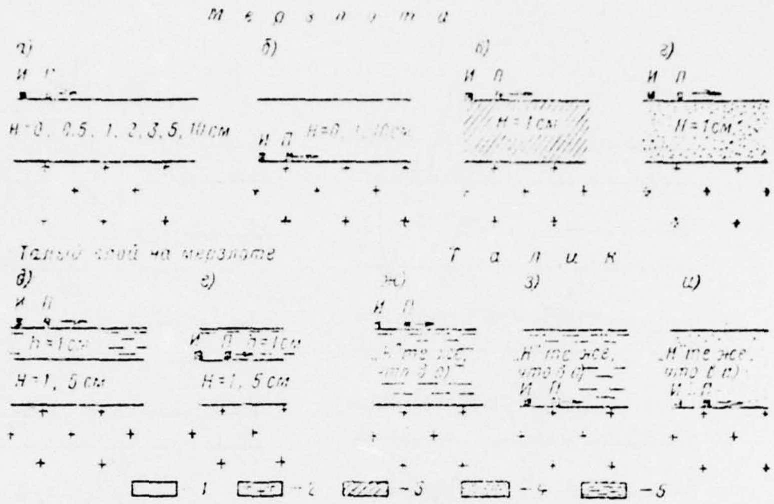

Figure 1. Principal diagrams of three-dimensional ultrasonic modeling of elastic waves with a layer (layers) on a half-space: 1 - ice; 2 - granite; 3 - loam; 4 - sand; 5 - water; I -- radiator; R -- receiver of ultrasonics a - Frost; b - Thawed water on frost.

according to B. N. Ivakin, such models belong in the first group and for them the constants of similarity of the frequency time depends only on the constant of geometric similarity:

$$C_t = \frac{H_n}{H_M} = C_l, \quad C_\omega = \frac{1}{C_l}.$$

We are studying a layer on a half-space. A body, the linear dimensions of which are greater than (2-3) λ, where λ is the wave length, can be considered a half-space for the study of seismic processes. For purposes of engineering seismic prospecting in nature, of interest is the case of variation of the layer thickness H = 0 - 100 m (H/λ = 0-3). If in the model H_m = 0 - 10 cm (H/λ = 0-3), then C_t = 1000; $C_\omega = 10^{-3}$. If in nature $\omega \approx 100$ Hz, then in work on the models the wave frequencies must be of the order of 100 kHz.

During ultrasonic modeling an IPA-59 seismoscope was used, and the radiators and receivers (hydraulically and thermally insulated) had a natural frequency of 150-200 kHz. The visible frequencies of the waves on the recording varied: 100-130 kHz (Rayleigh and transverse waves in granite and frozen layers) and 170-180 kHz (a forward wave in water). Experiments on frozen models were conducted in winter in the open air at from -10 to -15°C. For ultrasonic profiling the radiator was set at the zero point and the receiver was moved with a step of 2 cm. The radiator and receiver were moistened with water and frozen to the model, and that assured good acoustic contact. Two recordings were obtained at each point: with a large amplification of the registering apparatus (distinct first arrivals of waves) and lesser amplifications (resolved recording of subsequent waves). The obtaining of seismograms with "strong"

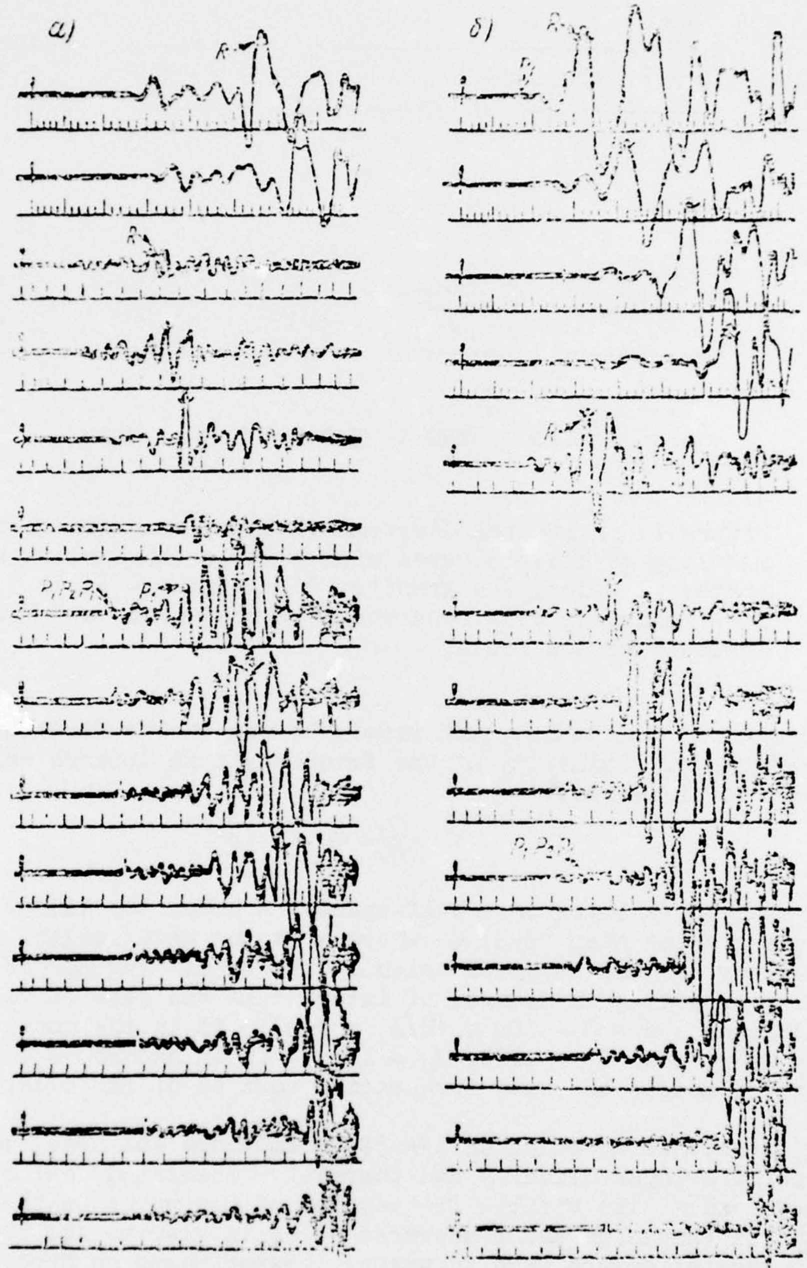

Figure 2. a - Oscillogram of ultrasonic profiling on the surface of frozen sand, $H_s = 4$ cm; b - Oscillogram of ultrasonic profiling on the surface of ice, $H_{ice} = 5$ cm.

and "weak" recordings is characteristic of the method of engineering seismic prospecting. The wave picture was photographed from the screen of the seismoscope. Examples of recordings are presented on Figures 2 and 3. Presented below is a description of the main characteristics of the wave picture according to the data of modeling for conditions characteristic of seismic prospecting in regions of the Extreme North and permafrost (Figure 1). Examples of travel time curves of the principal types of waves are shown on Figures 4-5.

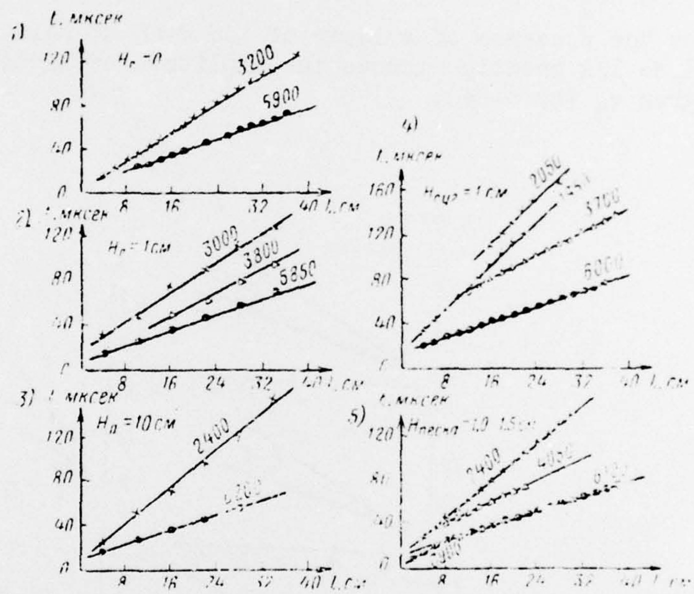

Figure 4. Travel time curves of the principal types of waves in profiling zz on frost. 1-3: profiling on a half-space loaded with a layer (diagram b, Figure 1); 4 - profiling on a half-space of loam (diagram c, Figure 1); 5 - profiling on the surface of sand (diagram d, Figure 1). a - microseconds

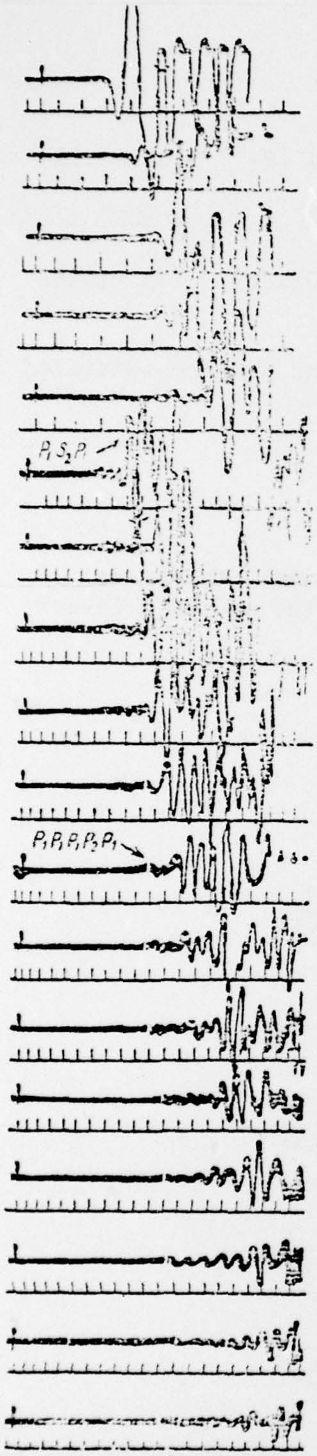

Figure 3. Oscillogram of ultrasonic profiling on the surface of water, H_w = 2 cm.

A layer of ice on a frozen half-space (profiling on the surface of ice, Figure 1a). At a layer thickness H = 0-1 cm the recordings are strong and not complicated by interference: 2 or 3 period (2-3)T oscillation of the longitudinal P_2 wave

in granite (v_{p_2} = 5900-6100 m/sec, f = 125-150 kHz) and (2-3) T of oscillation of the Rayleigh R wave (v_{R_2} = 3200 m/sec at H = 0 cm, v_R = 3000 m/sec at H = 0.5 cm, v_R = 2950 m/sec at H = 1 cm; f = 100-120 kHz). The ratios of the maximal amplitudes of oscillations are:

a) A_{R_2}/A_{p_2} = 10-20 (at H = 0 cm) in both the air-dry and the ice-saturated blocks:

b) A_R/A_{p_2} = 5-8 (at H = 0.5 cm);

c) A_R/A_{p_2} = 2-3 (at H = 1 cm).

Thus the presence of a layer of ice even of relatively small thickness $H/\lambda_R \leq 1/2$ greatly reduces the amplitude of Rayleigh waves and to a lesser degree v_R (by 6-8%).

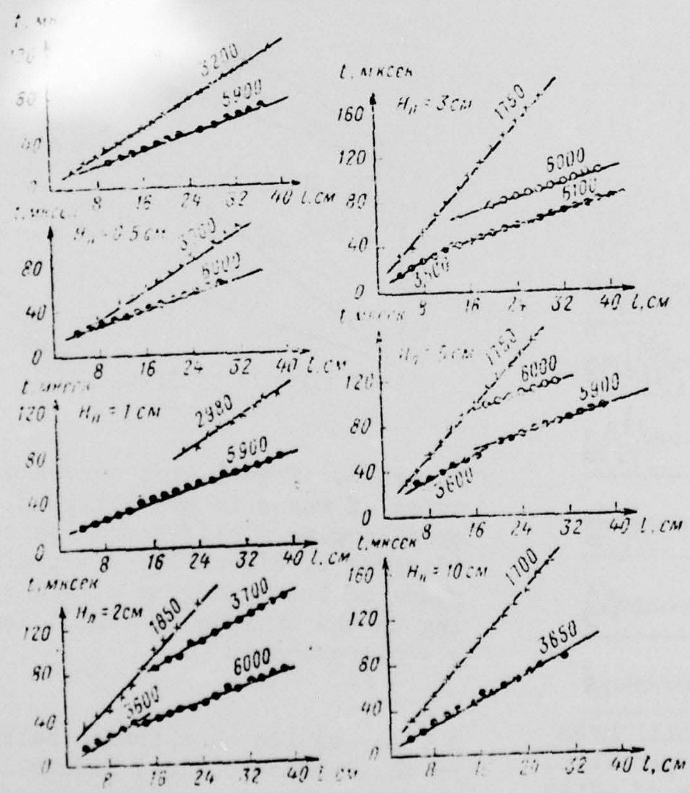

Figure 5. Travel time curves of the principal types of waves during profiling zz on frost, on the surface of a layer (diagram of Figure 1a). a - microseconds

At H $\geqslant$ 2 cm on recordings of profiling are visible (1-2) T oscillations of a forward longitudinal wave in ice (v_{p_1} = 3500-3700 m/sec, f = 170-190 kHz), a longitudinal refracted wave in granite (v_{p_2} = 6000-6100 m/sec, f = = 125-160 kHz) and a Rayleigh wave in a layer of ice (v_{R_1} = 1700-1800 m/sec, f = 100-125 kHz), the amplitude of which is 10-15 times as large as A_{p_2}. An interesting feature of the oscillograms is the presence on many of them of recordings of multiple reflected-refracted waves (1-2) T of oscillations with v = 5900-6100 m/sec, f = 125-140 kHz, the amplitude of which is 2-4 times greater than A_{p_2}. The wave was registered in different arrangements of observations (Figure 1) at distances of more than 8-10 cm from the radiator, with receivers satisfying single or double reflection from a free surface.

An ice layer on a frozen half-space (profiling on the surface of the half-space). Three principal waves were found on the recordings: longitudinal in granite -- (1-2) T oscillations with v_{p_2} = 5900-6100 m/sec, f = 125-140 kHz; a longitudinal wave in ice -- 2T oscillations with v_{p_1} = 3700 m/sec, the amplitude of which is 1.5-2 times larger than A_{p_2}; a Rayleigh wave with f = 110-125 kHz. A_R/A_{p_2} = 5-10 at distances near the radiator and A_p/A_R = 2-5 at distances remote from the radiator. The velocity v_{R_2} = 3000 m/sec (H = 1 cm) and on travel time curves of different phases of the R wave v_R = 2100-2400 m/sec (H = 10 cm).

Thus in the presence of a layer on a half-space a Rayleigh wave registered on the surface of the half-space is damped with distance considerably more than on a free half-space, and v_R decreases with increase of H.

A layer of frozen sand and loam on a frozen half-space (profiling on the surface of the layer). The wave picture with respect to frequencies and amplitudes is similar to the above-considered case of an "ice layer on a half-space." However, during profiling on sand and loam stronger damping of the field with distance is observed and a recording of oscillations less stable in form in comparison with the profiling on ice. Visible on the recordings are (2-3) T oscillations of a forward wave in the layer (sand -- v_{p_1} = 3900-4050 m/sec, loam -- v_{p_1} = 3700 m/sec, f = 100-140 kHz), of a refracted wave in granite with v_{p_2} = 6000-6100 m/sec, f = 125-140 kHz. A_{p_1}/A_{p_2} = 2-3; of a Rayleigh wave in a bed (sand -- v_R = 2400 m/sec, loam v_R = 1950-2000 m/sec, A_{R_1}/A_{p_2} = 10-20) and, starting with 24-26 cm from the radiator, a Rayleigh wave with v_R = 2850 m/sec and an amplitude 2-5 times greater than A_{p_2}. At greater distances from the radiator there is no deterioration of the Rayleigh wave packet (the phase velocity of different extremums corresponds to v_R of sand or loam).

A water layer on frost (Figure 1, e and f). A characteristic feature of the wave picture is a predominance of longitudinal waves: in ice with v_p = 3600-3700 m/sec (at negative temperatures) and v_p = 3200-3300 m/sec (melting ice), f = 140-200 kHz; in granite, refracted and reflected-refracted with v_{p_2} = 5800-6100 m/sec, f = 125-140 kHz and in water with v_p = 1450-1500 m/sec, f = 100-110 kHz.

Whereas the first two waves are of approximately identical intensity, the amplitude of that in water is approximately 8-10 times greater. In a layer of ice of 5 cm and during profiling on the surface of the water an exchange PSP wave also is positively registered, propagating over the ice with a phase velocity of 1900 m/sec, f = 110-125 kHz.

A thawed layer on a thawed half-space (Figure 1, g,h,i). In water-saturated granite v_p = 5300 m/sec and v_R = 2810 m/sec. During profiling on the surface of water (Figure 1g) (2-3)T oscillations were registered: a very intense forward longitudinal wave in water (v_p = 1450-1500 m/sec, f = 100 kHz, refracted and reflected-refracted waves corresponding to the surface of granite (v_{p_2} = = 5350-5400 m/sec, f = 120-140 kHz) and an exchange wave $P_1S_2P_1$ with v = 2900 m/sec, f = 100-120 kHz. The amplitude of the latter is 6-12 times A_{p_2}. The amplitude of the reflected-refracted wave exceeded A_{p_2} by 2-3 times. During profiling on the surface of granite (Figure 1h) (2-3) T oscillations were registered: a longitudinal (v_{p_2} = 5200-5400 m/sec, f = 125-150 kHz), a reflected-refracted with a greater amplitude than A_{p_2}, and also a Rayleigh wave. The phase velocity of the R wave diminished slightly with increase of H: from 2810 m/sec (H = 0 cm) to 2690 m/sec (H = 10 cm). The loading of the half-space with a layer of water has a great influence on the change of A_R: whereas at H = 0 A_R/A_{p_2} = 8-10, at H = 5-10 A_R/A_{p_2} = 2-4, and in the presence of the layer the damping of the Rayleigh wave increases with distance.

During profiling on the surface of granite in the presence of a layer of water-saturated sand on it (Figure 1i), as in the case considered above, a longitudinal and a Rayleigh wave were registered in granite. With increase of the layer thickness V_R decreased: 2810 m/sec (H = 0 cm), 2700 m/sec (H = = 1 cm), 2330 m/sec (H = 5 cm) and 2100 m/sec (H = 10 cm). The ratio A_R/A_p during the loading of the half-space with a sand layer decreased to 2-5 (at H = 5-10 cm) and the R-wave damping increased with distance.

3. Study of the Dispersion of the Velocity of Rayleigh Waves in a Layer on a Half-space With Reference to Problems and Conditions of Engineering Seismic Prospecting

Calculating Dispersion Curves

We will examine a layer (medium 1) on a half-space (medium 2). It is known from seismology [4, etc] that the phase velocities of short Rayleigh waves approach v_R in a layer (since short waves do not penetrate deeply), and the phase velocities of very long waves approach v_R of the half-space. Let us turn to a solution, known from the theory of elasticity [6], of the problem of propagation of transverse waves in a layer with the thickness H on a half-space:

$$\operatorname{tg}(\varkappa_1 H) = \frac{G_2\varkappa_2}{G_1\varkappa_1},$$

where

$$\varkappa_1 = \omega\sqrt{\frac{1}{v_{s_1}^2} - \frac{1}{v_s^2}}; \quad \varkappa_2 = \omega\sqrt{\frac{1}{v_s^2} - \frac{1}{v_{s_2}^2}};$$

$\omega = 2\pi/T$ is the circular frequency; T is the period; G_1 and G_2 are the shear moduli, v_{s_1} and v_{s_2} are the transverse wave velocities in the layer and the half-space; v_s is the transverse wave velocity in the layer on the half-space (along the surface of the layer).

Equation (1) determines in implicit form the dependence of v_s on the frequency; it has solutions only at real values of $\varkappa_1$ and $\varkappa_2$, so that it always happens that $v_{s_2} > v_s > v_{s_1}$. Therefore the propagation of the type of wave under consideration is possible only at $v_{s_2} > v_{s_1}$. We will write (1) in the expanded form:

$$\mathrm{tg}\left(2\pi \frac{H}{\lambda} \sqrt{\frac{v_s^2}{v_{s_1}^2} - 1}\right) = \frac{v_{s_2}^2 \delta_2}{v_{s_1}^2 \delta_1} \sqrt{\frac{1 - \frac{v_s^2}{v_{s_2}^2}}{\frac{v_s^2}{v_{s_1}^2} - 1}},$$

where δ_1 and δ_2 are the densities of the layer and the half-space. All values

, where n = 1,2, ..., are discarded.

For the conditions of seismic prospecting of small depths the ratio v_R/v_S varies in a relatively narrow range (0.91-0.94), and under permafrost conditions (a frozen icy layer on the same half-space) in still narrower limits (0.925-0.935). Therefore we will write (1a) in a form convenient for further analysis and comparison with experiment:

$$\mathrm{tg}\left(2\pi \frac{H}{\lambda} \sqrt{\frac{v_R^2}{v_{R_1}^2} - 1}\right) = \frac{v_{R_2}^2 \delta_2}{v_{R_1}^2 \delta_1} \sqrt{\frac{1 - \frac{v_R^2}{v_{R_2}^2}}{\frac{v_{R_2}^2}{v_{R_1}^2} - 1}}.$$

Equation (2), determination of v_R, was solved on an M-20 computer with the following values of the parameters included in it:

> $\delta_2/\delta_1 = 1.5$; v_R = 1200 m/sec - 4000 m/sec (steps of 400 m/sec);
> v_R = 100 - 2000 m/sec (steps of 200 m/sec) for the values $v_{R_2} > v_R$;
> H/λ = 0 - 10 (at H/λ = 0 - 0.5 a step of 0.05, at H/λ = 0.5 - 1 a step of 0.1 and at H/λ = 1 - 10 a step of 1).

Examples of dispersion curves are shown on Figures 6-8. At the relatively low values v_{R_1} = 0.1 - 0.5 km/sec (which is characteristic of thawed unconsolidated deposits) the values of v_R decrease sharply from v_{R_2} to v_{R_1} during change of H/λ from 0 to 0.2-0.3. Characteristic of a frozen layer (v_{R_1} = 1.5-2.0 km/sec) on a half-space is a smoother change of v_R from v_{R_2} to v_{R_1} at H/λ = 0 - 1.

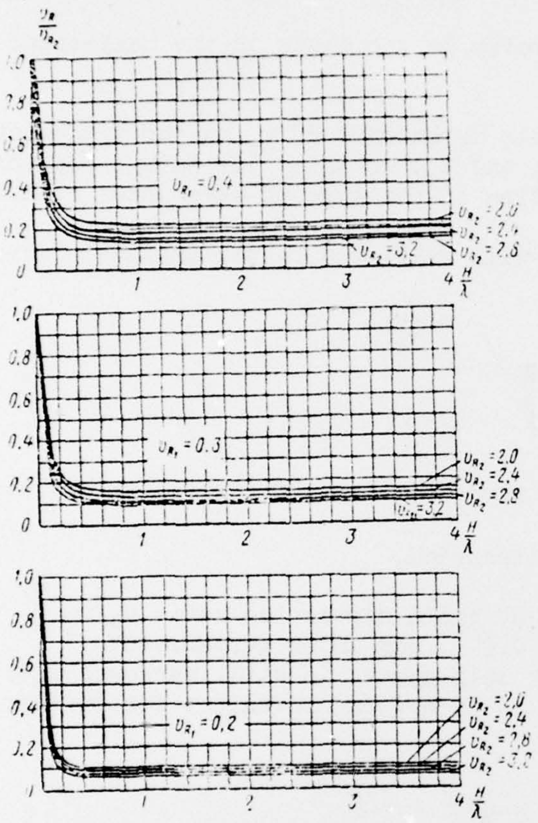

Figure 6. Dispersion of Rayleigh wave velocities v_R in the layer on a half-space. v_{R_1} -- the velocity of Rayleigh waves in the layer, km/sec; v_{R_2} -- the velocity of Rayleigh waves in the half-space, km/sec.

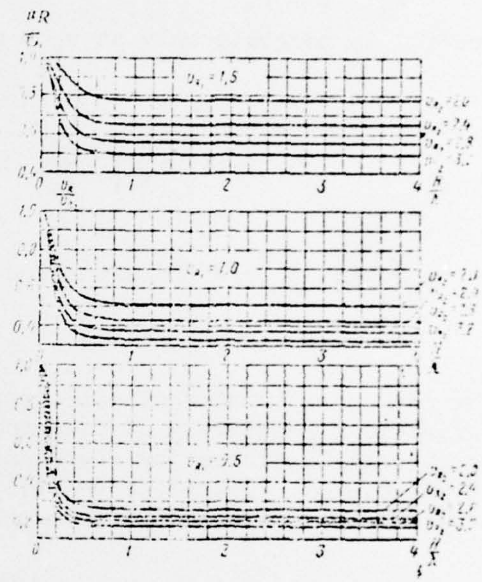

Figure 7. Theoretical dispersion curves of the Rayleigh wave velocity v_R in the layer on a half-space. v_{R_1} and v_{R_2} as on Figure 6.

Experimental Data on the Dispersion of the Velocity of Rayleigh Waves in Permafrost Regions

Rayleigh waves registered during shallow seismic prospecting in a permafrost region have been described in a number of works [1, 2]. Characteristic of each region is a relatively narrow range of their frequencies and considerable changes of frequency of R-waves are observed only in the transition of a wave from a region of frosted rocks into a region of thawed rocks [2], which is a reliable sign for the discovery of taliks. The amplitude of R-waves, as a rule, are 5-15 times as large as the amplitudes of forward and refracted longitudinal waves. Presented below are seismic prospecting data on the

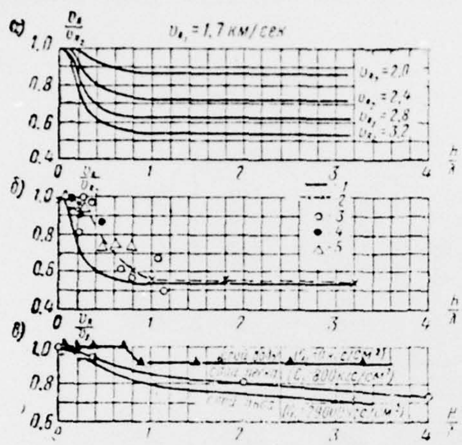

Figure 8. Dispersion of the velocity of Rayleigh waves v_R in the presence of a layer on a half-space: a - calculating dispersion curves at different v_{R_2} in the half-space and at a v_{R_1} of the layer of 1.5 km/sec; b - dispersion of v_R in a frozen layer on a frozen half-space: 1 - theoretical curve (ice on granite); 2 - experimental curve (ice on granite) according to ultrasonic modeling; 3, 4 & 5 - data of seismic prospecting in permafrost regions: basins of the rivers Vilyuy, Indigirka and Kolyma respectively; 6 - dispersion of v_R in the semi-space (ultrasonics on the surface of granite) in the presence of layers of water, wet sand and ice on it.

dispersion of v_R in permafrost regions (Table 1). The values of v_R were calculated by the method of the difference travel time curve, which made it possible to exclude the influence on v_R of difference in the installation of seismic receivers and local heterogeneities in the upper part of the profile. To exclude the influence on v_R of heterogeneities of a different type in the layer and half-space (variations of granulometeric composition, iciness, temperature in the layer, and differences in the degree of fracturing of the half-space -- the bedrocks) within the region of investigations in the given range of value of H we calculated the average weighted value of v_R along the survey lines. Due to difference in the length of the survey lines for each range of H values the calculated values of v_R, generally speaking, are not of equal accuracy. The values of v_R were determined on sections with minimal values of H/λ. As a rule v_{R_2} is 5-10% lower than v_R in preserved ice-saturated samples of corresponding rock at the given temperature.

The Vilyuyskaya GES. The base was composed of fine-grained and medium-grained dolerites of the Lower Mesozoic (T_1). The thickness of the belt of weathering of the rocks is from 0 to 30 meters. Unconsolidated thick deposits, as a rule, consist in the first few meters of loams, more rarely of sand loams, clays and sands. The thickness of the permafrozen rocks in the banks of the Vilyuy River valley is 150-200 meters. The temperature t_p of the permafrozen rocks on the investigated section at depths of 15-20 meters is about -2 to -3°C. The average characteristics of the half-space (the rocks below the belt of weathering) are: v_{p_2} = 5000 m/sec and v_{R_2} = 2650 m/sec.

The Kolymskaya GES. The base is composed of quartz plagioclase granites (J_3 - Cr_1). The average thickness of the belt of weathering is 5 meters. The unconsolidated deposits consisted of sand, gravel and pebbles, and also sandy loams and loams (H = 0 - 30 m). The thickness of the permafrozen rocks was from several tens of meters to 200-300 meters; t_p = -6 to -8°C. The mean

Table 1 Rayleigh wave velocities in the region of the Vilyuyskaya GES, the Kolymskaya GES, the Deputatskiy Mining and Concentration Combine and the basin of the river Tatta

Район, наименование скальных пород	H (включая зону выветривания), м	Длина волны λ_R, м	H/λ_R	v_R, м/с	Длина сейсморазведочных линий, м	v_R/v_{R_1}
Вилюйская ГЭС (долериты)	5 — 6	40	0,14	2464	210	0,92
	7 — 8	38	0,16	2123	175	0,8
	12	47,2	0,25	2650	246	1
	15 — 17	46,5	0,34	2550	210	0,96
	20	26	0,77	1450	80	0,55
	25	22	1,14	1300	60	0,49
	35	33	1,07	1800	45	0,68
Колымская ГЭС (граниты)	5	53	0,095	3150	575	1
	8	57	0,14	2880	455	0,92
	10	59	0,17	2940	3105	0,93
	15	58	0,26	2920	2030	0,93
	20	46	0,44	2280	115	0,725
	25	46	0,55	2320	385	0,735
	35	46	0,76	2320	320	0,735
Колымская ГЭС (сланцы, параллельно сланцеватости)	10 — 14	69	0,17	2770	360	0,95
	15 — 19	59	0,29	2370	715	0,82
	20 — 24	58	0,38	2350	880	0,81
	25 — 29	56	0,48	2250	475	0,77
	30 — 34	55	0,58	2220	615	0,76
	35 — 45	53	0,75	2110	660	0,73
Колымская ГЭС (сланцы, вкрест сланцеватости)	10 — 14	65	0,18	2590	200	0,96
	15 — 19	57	0,30	2290	625	0,85
	20 — 24	54	0,41	2150	520	0,80
	25 — 29	48	0,56	1900	825	0,71
	30 — 34	53	0,6	2140	435	0,79
Депутатский ГОК (метаморфизованные песчаники)	3	26	0,11	2650	55	1
	5	24	0,19	2394	4375	0,905
	7 — 8	23	0,35	2340	455	0,88
	10	23	0,44	2310	1535	0,87
	13 — 15	21	0,66	1610	505	0,61
Бассейн р. Татты (песчаники)	45 — 50	30 — 40	1,25	1500	1390	0,75

Key: A - Region and type of rock B - H (including belt of weathering), m
C - Wave length λ_R, m D - v_R, m/sec E - Length of seismic survey lines, meters
1 - Vilyuyskaya GES (dolerites)
2 - Kolymskaya GES (granites)
3 - Kolymskaya GES (shales parallel to schistosity)
4 - Kolymskaya GES (shales across the schistosity)
5 - Deputatskiy Mining and Concentration Combine (metamorphized sandstones
6 - Basin of the river Tatta (sandstones)

values are v_{p_2} = 5600 m/sec and v_{R_2} = 3.15 km/sec. The section of the housing settlement is composed of metamorphized shales (T_3 - J_1) with a northwestern course. Their belt of weathering varies within considerable limits (from 5 to 30 meters). The unconsolidated deposits (H = 5-20 meters) consist of sand-gravel-pebble, more rarely loams and sandy loams. The seasonally thawed layer (in the working period up to 2-3 meters) is mainly loams and sandy loams. The basic temperature range is t_p = -1 to -3°C. The mean values of the elastic wave velocities are v_{p_2} = 5450 m/sec and v_{R_2} = 2900 m/sec along the schistosity and v_{p_2} = 4600 m/sec and v_{R_2} = 2700 m/sec across the schistosity.

The Deputatskiy Mining and Concentration Combine. The seismic prospecting was done in the valley of the Irgichan River (the Indigirka basin). The bedrocks are Upper Jurassic metamorphized sandstones with layers of clayey shales and siltstones. The belt of weathering in the flood-plain of the Irgichan River has not been established, but on the riverside slopes it does not exceed 2-3 meters. The unconsolidated deposits consist of sand-granite-pebble deposits and also of sandy loams and loams. The thickness of the permafrozen rocks in the region of the work is 200-300 meters and t_p = -6 to -8°C. The mean values are v_{p_2} = 4950 m/sec and v_{R_2} = 2650 m/sec.

The basin of the river Tatta (the Lena-Amga interfluve). The bedrocks are Middle Jurassic sandstones. The unconsolidated deposits of the section of investigations (H = 40-45 meters) are composed mainly of loams. The thickness of the permafrozen rocks exceeds 200 meters; t_p = -4 to -6°C. The bedrocks are characterized by a relatively low v_{p_2} of 3800 m/sec, which can be explained by the higher content of clay particles and unfrozen water in the sandstones. The values of v_{R_2} have not been determined, but if one starts from the possible values of μ_{d_2} of frozen icy sandstones, for such a value of v_{p_2} the value of $v_{R_2} \approx 2000$ m/sec.

Discussion of the Experiments

1. Comparison of the above-presented experimental data with the corresponding theoretical dispersion curve and the dispersion curve for the data of ultrasonic modeling shows (Figure 8b) that the theoretical and experimental curves differ at H/λ = 0.1 - 0.8. In that case the data of the field seismic survey on the Rayleigh wave dispersion (Table 1) agree well with the results of three-dimensional ultrasonic modeling. The experiment gives a smoother drop of v_R from the value v_{R_2} to v_{R_1} with increase of the thickness H of the layer on the half-space than follows from the theory. At $H/\lambda >> 0.9$ the theoretical and experimental curves coincide. The greatest scattering is given by points relating to the base of the Vilyuyskaya GES, and that is explained, in our view, by the relatively small length of the survey lines on which the mean values of v_R were determined. In spite of the fact that bedrocks of the above-considered regions have a different petrographic composition and structure and are characterized by different (but relatively high) values of v_{p_2} and v_{R_2} (the mean values are v_{p_2} = 4.6-5.6 km/sec and

v_{R_2} = 2.65-3.2 km/sec) the dependence v_R/v_{R_2} for all those rocks is a common one, which makes it possible to recommend its use in the practice of engineering seismic prospecting in new region. These are above all regions of the propagation of igneous and metamorphous rocks, and also sedimentary rocks, v_{p_2} and v_{R_2}, in which they fall in the above indicated range. For the basin of the river Tatta, where the sandstones were characterized by low values of v_{p_2} and v_{R_2}, v_R/v_{R_2} = 0.75 at H/λ = 1.25 agrees with the theoretical curve for the corresponding values v_{R_1} = 1.5 km/sec and v_{p_2} = 2.0 km/sec. Therefore to characterize the dispersion of v_R in regions of the propagation in relation to weak rocks (sandstones with clayey cement, argillites, etc) having relatively low values of v_{p_2} and v_{R_2} in a natural bedding (for example, sandstones of the Tatta River basin) it is advisable to use the calculating dispersion curve obtained for specific values of v_{p_2} and v_{R_2}. It should also be noted that the case of low-velocity propagation is rare for regions in which frost is widespread and occurs when in the above-indicated rocks water and air, and not ice, predominate as the filler of cracks and pores.

2. In the ultrasonic modeling an investigation was made of the influence of the loading of the half-space on the propagation of surface waves along the boundary of the layer -- the half-space (Figure 1 b,d,h,i). The dispersion of the surface wave velocity was studied (Figure 8c). In the presence of a layer of water it is manifested, starting with $H/\lambda > 0.7$, and v_R is reduced by approximately 10%. This must be borne in mind in studying the elastic properties of water-saturated samples of rocks. In the measurement of v_R in them it is necessary that the water layer on it be thin ($H < 0.7\lambda$), otherwise we obtain reduced values of v_R. And to exclude in addition an intensive wave -- noise on the water, the water layer above the sample should be reduced to a minimum (less than 1 mm).

When the half-space is loaded with a layer of water-saturated sand and ice a stronger reduction of v_R is revealed than in the case of a layer of water (Figure 8c). By comparing the obtained dispersion curves with one another it can be concluded that the surface wave velocity along the layer-half-spece contact differs all the more from v_{R_2} (in the half-space) the greater the shear modulus of the layer (for water G_d = 0 kg(force)/cm^2, for water-saturated sand 800 kg(force)/cm^2 and for ice 29,000 kg(force)/cm^2.

3. Comparison of the seismograms obtained under permafrost conditions [1,2, etc] with the data of three-dimensional ultrasonic modeling convinces one that both in absolute values of the longitudinal and Rayleigh wave velocities, distinctive features of the travel time curves of forward and refracted waves, and in the correlation of the amplitudes of P and R waves and in the correlation of their frequencies a complex picture is observed. Complete identity is observed in the correlation of the kinematic characteristics. With respect to dynamic characteristics of the wave picture it should be noted that the

oscillograms obtained for the case of "ice on a half-space" are more similar to seismograms for the case of "frozen unconsolidated deposits on a frozen half-space" than oscillograms of ultrasonic modeling, when the layer was of frozen sand or frozen loam. For the latter a strong damping of longitudinal and surface waves with distance was observed, whereas recordings on an ice layer were more stable. A reason for anomalous damping in sand and in loam is heterogeneities of the structure of those layers, which at ultrasonic frequencies can be commensurable with λ. The more homogeneous structure of ice corresponds better in that respect to the case of field seismic prospecting investigations (the size of the heterogeneities in unconsolidated deposits is much smaller than λ). The data of modeling and seismic prospecting testify to the advisability of using for determination of E_d, G_d and μ_d under permafrost conditions Rayleigh waves characterized by very great intensity on the recordings. High-frequency recordings of R waves can be used to calculate the elastic constants of frozen Quaternary deposits. And to determine the elastic properties of rocks hidden under alluvia the low-frequency oscillations should be registered if possible, as in that case the registered value of v_R differs little from the v_R of the rocks.

4. The wave picture in modeling for talik conditions was compared with the corresponding description of the principal types of waves registered during engineering seismic prospecting [1,2]. Complete similarity was established with respect to the absolute values of the velocity, characteristics of the time travel curves and correlations of the amplitudes and frequencies of different waves. Under conditions of thawed rocks the main information about the velocities of transverse waves in rocks hidden under a layer of alluvia or water is borne by intensive exchange refracted waves, and at low values of H/λ, also by Rayleigh waves.

5. In three-dimensional ultrasonic modeling in the presence of either a solid or a liquid layer on the half-space, in subsequent arrivals a wave with a boundary velocity v_{P_2} (the velocity in the half-space) and with an amplitude 2-4 times as large as that of the $P_1P_2P_1$ was registered. According to the conducted investigation it is a multiple reflected-refracted wave which has been reflected from the boundary of the layer -- air, and not $S_1P_2S_1$, as is indicated hypothetically in [1].

6. The work done makes it possible to determine more precisely a characteristic important for engineering seismic prospecting -- the "depth of trapping" of elastic oscillations [8] in relation to transverse and surface waves in the layer on the half-space. Actually, the value of H/λ on the dispersion curve, starting with a certain value of v_R/v_{R_2}, does not depend on H/λ, and that means that, starting with that value of H, an elastic wave does not capture the half-space. In a recent work [8] the depth of capture H_2 is estimated by A. I. Savich at 0.25λ irrespective of the type of waves and the elastic characteristics of the studied media. Analysis of the theoretical and experimental dispersion curves obtained by us makes it possible to conclude regarding H_3 for R and S waves in a layer on a half-space:

1) if v_{s_2} (in the half-space) is larger than v_{s_1} (in the layer) by an order of magnitude or more, then $H_3 \approx (0.2 - 0.3)\lambda$, which coincides with the above-indicated value 0.25λ; 2) if $v_{s_2}/v_{s_1} = 5 - 10$, then $H_3 \approx (0.3 - 0.5)\lambda$; 3) if $v_{s_2}/v_{s_1} = 3 - 5$, then $H_3 \approx (0.5 - 0.8)\lambda$; 4) if $v_{s_2}/v_{s_1} = 1.1 - 2$, then $H_3 \approx \lambda$.

7. During ore and petroleum seismic prospecting in a permafrost region surface waves usually are regarded as noises and are not used in the interpretation. It also is known that the thickness of unconsolidated deposits under permafrost conditions is determined with great errors in many cases. Then, in essence, the question arose of determining the thickness of the frozen layer on a frozen half-space. The use of information which can give dispersions of the Rayleigh wave velocity to solve that problem will make it possible to construct seismogeological profiles more substantiatedly. For that purpose we will use a dispersion curve (Figure 8b) characteristic of most regions of permafrost. If we know the mean value of v_{R_2} for the rocks of the given region, on the basis of values of v_R and λ_R determined during seismic prospecting and the calculated value of v_R/v_{R_2}, we find the value of H/λ_R and later of H. The value of H is the mean for the interval of the seismic prospecting profile on which v_R was determined. The length of such an interval must be at least 100 meters. In order, in determining H, to deal with the region of the dispersion curve with $H/\lambda = 0-1$, Rayleigh waves with a wave length $\lambda_R \geqslant H_{max}$ should be registered, where H_{max} is the maximally possible thickness of the frozen unconsolidated deposits on the section of the work.

Principal Conclusions and Recommendations

1. In determining the elastic properties (E_d, G_d and μ_d) of unconsolidated and solid rocks in permafrost regions by seismic prospecting it is advisable to use, besides longitudinal, Rayleigh waves (on frost) and exchange waves (in taliks). In the presence of a layer of frozen unconsolidated deposits on bedrocks it is necessary to take into consideration the dispersion v_R as a function of the layer thickness and the length of the used waves. Understatement of the dispersion leads to greatly reduced values of E_d and G_d and overstated values of u_d of the rocks.

2. To determine the elastic constants of the massive rock covered by frozen alluvia one should, if possible change to the registration of low-frequency Rayleigh waves, since in that case v_R differs little from v_{R_2} (in the rocks).

3. In the investigation of various questions about the application of seismic prospecting in a permafrost region the ultrasonic modeling of wave fields on three-dimensional models of natural materials (granite, ice, sand, loam, etc) is promising. Good agreement has been obtained of kinematic and dynamic features of the wave picture according to the data of modeling and field seismic prospecting work.

4. The Rayleigh wave in a layer on a half-space, the dispersion v_R of which is used to calculate the elastic constants of rocks, under frost conditions has an amplitude 5-20 times as great as that of a longitudinal wave only at a layer thickness $H < (0.3 - 0.5)\lambda$.

When the layer thickness is greater A_R is commensurable with A_p and the phases of a Rayleigh wave with a large amplitude (10-20 times greater than A_p) bears information about the Rayleigh wave velocity in the layer. In the presence of a layer with $H \geqslant \lambda/3$ close to the radiator only a Rayleigh wave is registered in the layer, and a dispersion of the phase velocity is observed at a certain distance from the point where the oscillations are excited (for conditions of engineering seismic prospecting, of the order of 200 meters or more).

5. In the presence of a thawed layer of small thickness on frost an intensive wave, registered in "subsequent arrivals," is an interference $(R + P_1S_2P_1)$ wave. In the presence of a layer of water on a frozen medium or thawed half-space information about v_s is born by intensive waves of the type $P_1S_2P_1$. Under the conditions of "a thawed layer on a thawed half-space" information about v_s of the half-space is borne by $P_1S_2P_1$ and $P_1S_2S_1$ waves [7,3].

6. Dispersion curves of the Rayleigh wave velocities, calculated with formulas of elasticity theory for the case of "a layer on a half-space," give a more rapid drop of v_R from v_{R_2} to v_{R_1} at $H/\lambda = 0.1 - 0.8$ than follows from the data of field investigations in the rock mass and ultrasonic modeling. At $H/\lambda > 0.9$ the calculating and experimental curves coincide. The data of seismic prospecting and three-dimensional ultrasonic modeling coincide.

7. The dispersion curve $v_R/v_{R_2}(H/\lambda)$ obtained from modeling and confirmed by seismic prospecting data is recommended for determination of v_{p_2} (in rocks) in most permafrost regions for which the mean values are $v_{p_2} > 4.6$ km/sec and $v_{R_2} > 2.65$ km/sec. In the case of a low-velocity half-space a calculating dispersion curve for specific mean values of v_{R_1} and v_{R_2} of the given region should be used.

8. In permafrost regions the transition from a section of frozen rocks to a talik is accompanied by a sharp reduction of v_R. The drop of v_R is stronger the greater the thickness of the covering bed H.

9. An approximate estimate of the value of E_d of permafrost icy rocks can be made on the basis of measurements of v_{p_2} in two ways:

a) having taken mean values of u_d equal to: 0.3 (igneous and metamorphous rocks), 0.20 (quartz sandstones), 0.26 (arkose sandstones) and 0.35 (limestones);
b) on the basis of charts of the connection of E_d and v_p of rocks of a given region (the values of v_p and E_d necessary for construction of the diagram are determined during seismoacoustic work in adits and wells and on outcrops where the registration of v_s or v_R presents no difficulties).

10. During measurement of v_R in water-saturated samples of rocks it is necessary that the water layer on them be minimal (better up to 1 mm) for reduction of the dispersion v_R and that recordings not be complicated by an intensive wave in water.

11. It is advisable to use the dispersion of Rayleigh waves in a permafrost region also in the construction of seismogeological profiles.

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